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Evolutionary Game Model of Strategic Maritime Transport Passages: A Case of the Strait of Hormuz

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Abstract: Given the in-depth advancement of the "Belt and Road" initiative, cooperation among countries along the initiative is increasing. The strategic maritime transport passage is closely related to the interests of relevant countries. The games between countries along important transport passages in terms of the pursuit of geopolitical rights and interests occur frequently. This paper establishes an evolutionary game model of the strategic maritime transport passages taking the Strait of Hormuz as an example and explores the game of the countries on both sides of the strait. By analysing their behaviour and possible strategies, the evolutionary stable strategy for each country is obtained. Recommendations are made to aid with the relevant rights and interests of related countries.

Keywords: strategic maritime transport passage; evolutionary game; evolutionary stable strategy; Strait of Hormuz

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1. Introduction

Strategic Maritime Transport Passages (SMTPs) play a vital role in transporting cargo around the world. They are not only related to the transportation of goods and energy but also affect the military, economic, and maritime rights and interests of a country or region. Many countries in the world need to utilize these SMTPs for the transportation of resources to meet their own trade demand. Once a certain SMTP is blocked, the economy of the related countries, and potentially the world, can be negatively affected, such as the blocking of the Suez Canal in March 2021. When political or trade frictions occur between countries, SMTPs can be used as support for coastal countries and can even be used as transport passages for strategic materials. Historically, there have been battles for passages to ensure the smooth transportation of strategic materials.

The importance of SMTPs depends on several factors, such as their ability to transport goods to various countries in the world, the productivity of the coastal countries in the region, and the significance of military strategies for some countries [1,2]. The Strait of Hormuz has long been a hub of culture, economy, and trade between Eastern and Western countries. It is also currently one of the busiest waterways in the world. It is well known that Middle East and Gulf countries have the richest oil resources in the world. If these countries wish to trade and transport oil and gas, and other resources, then the Strait of Hormuz is the only channel that can reach the outside world. Due to many reefs and shoals in the area, the operational width of the transport passage is limited, and the smooth flow of traffic through the strait is also a matter of concern to various countries. In the Belt and Road Initiative (BRI), China proposes actively promoting the cooperation and development of countries along the initiative, as well as to realizing the interconnection of development among countries, and SMTPs are indispensable strategic fulcrums. In the mid-1980s, the US government claimed to control 16 strategic passages in the world, including the Strait of Hormuz [3]. Huang et al. (2021) identified the Strait of Hormuz as the most significant passage in the context of China's BRI [4]. Therefore, the Strait of Hormuz is currently one of the most important transport passages in the world, in terms of economic significance or strategic importance. Along with the continuous development of the world economy, every country in the world pays great attention to SMTPs to protect its own rights and develop its own economy, thus frictions between countries inevitably appear. Disputes between countries surrounding SMTPs have also intensified. In these strategic passages, the game between countries has always existed. In the case of the Panama Canal, the economic and military value of the Canal has provided greater convenience to the Occident. During the 19th century, the US, the United Kingdom, and France argued over the cutting, operation, and control of the Panama Canal [5]. The Strait of Malacca has long been a focus of attention for world powers because of its strategic importance. During the period of US–Soviet hegemony, the Strait of Malacca was fiercely contested by both sides to prevent oil shipments from being restricted [6].

Currently, the value of the passage, the sovereignty of the passage, and the benefits it can bring have always been the focus of each country's maritime strategy in the game between countries around strategic passages [7]. Therefore, every country should develop a strategy to mitigate against unexpected situations and events relating to strategic passages. The security of SMTPs has been one of the areas of great concern for researchers [8]. The specific influencing factors include economic, political, and military aspects. These influencing factors constrain each other and create a linkage between them. In this research, the specific game-playing process between different countries is studied and the possible consequences are discussed through a quantitative analysis.

This research proposes an evolutionary game model to analyse the game between the countries associated with SMTPs, taking the Strait of Hormuz as an example. The reasons and results of several conflicts between the United States (US) and Iran as well as the factors including their geographical location and military strength in the Strait of Hormuz are analysed in Section 3. In Section 4, the evolutionary game model is built. In the subsequent section, the evolutionary stable strategies of the two governments are discussed in different situations. In Sections 5 and 6, each scenario is analysed and simulated in order to obtain a more intuitive view of the evolutionary path in each scenario.

2. Literature Review

2.1. Geopolitical Analysis of Strategic Maritime Transport Passages

The research on strategic passages mainly involves the value identification of strategic passages, the geopolitical analysis of passages, and the cooperation and competition of passages between countries [9–12]. The essence of geopolitics is the pursuit of geopolitical rights and interests by countries to protect their interests. In the modern international situation, the attention of most countries to SMTPs is by no means confined to its surroundings. Li compared the ideas of some major countries towards strategic passages and combined the historical factors of these passages [13]. Through comparing the strategic passage thinking of the major powers in the world, the geopolitics of these strategic passages are discussed in detail one by one.

In terms of the importance of strategic corridors for each country, Katzman et al. (2012) explored the importance of the Strait of Hormuz in global transportation [14]. They mainly analysed the political attitudes of countries towards the strait, including the US, Iran, Canada, and the United Kingdom. Garamond (2015) conducted research based on maritime security geostrategy [15]. The results showed that whether a strategic passage could be unblocked was directly affected by the geographical location and geopolitical factors of the strategic transport passage. Blanchard (2017) summarized the content and scope of China's Maritime Silk Road strategy and analysed the geopolitics of some strategic passages that diverged from it [16].

The current research on strategic passages in China mainly focuses on the geopolitics and transportation capabilities of the passages and discusses their value from the economic and strategic aspects [17]. The game between the countries involved in the strategic passages has mostly been analysed qualitatively in previous research, and there is limited quantitative research on specific games. In order to determine the value of strategic transport passages, Lee et al. (2018) studied the main transport corridors in the BRI and their impact on China's trade. This study identifies economic and transport corridors, dry ports, and city clusters as key elements of the BRI and confirms that the development of the corridor will gradually extend to the hinterlands [18]. In the same year, Yang et al. (2018) conducted a study on the relative performance of two emerging trade corridors along the BRI. The data therein was examined and analysed through fuzzy multi-criteria decision analysis, exploring the development of the routes in different scenarios. The study concluded that oil price volatility and the infrastructure development of transport companies would have an impact on the relative performance of transport routes [19].

2.2. Evolutionary Game Theory

In the early 1970s, Smith and Price (1973) first proposed the concept of Evolutionary Stable Strategy (ESS) in evolutionary game analysis. It is an important step forward for the development of evolutionary games [20]. In the subsequent development, Borger (2007) proved that the learning model converged to its replication dynamics in a continuous time through the continuous learning of the participants in the game environment. Replication dynamics and stable strategies have gradually developed into the main content of the evolutionary game theory [21].

At present, evolutionary game theory is mainly applied to research areas with a relatively large composition base and a more complex research environment [22]. It mainly analyses the strategies that different groups may adopt with an evolution process of their chosen strategies, and research tends to focus on the ESS of the game subject in different game situations [23].

For the evolutionary process to be closer to the actual situation, Weibull pointed out that people tended to pay more attention to the methods and instruments used in the game [24–26]. Once the external environment changes, each subject will have a different probability to alter its strategy combination. Boccabella (2017) further considered the calculus model of evolutionary games [27]. Through this model, the evolution of different populations in mixed strategies was described. The stability and the asymptotic of different strategies were analysed in detail.

Evolutionary game theory is widely applied in many industries [28–30]. Ozkan-Canbolat (2016) utilized evolutionary game theory to analyse strategic innovation, which determined whether other participants were finitely rational when making strategic choices for those involved [28]. This helped the decision makers to choose the optimal strategy. Jian (2018) took the Chinese manufacturing industry as the subject of their study and built an evolutionary game model to analyse stabilization strategies under different stages using replicated dynamic systems [29]. The results suggested that China needed to be prepared for the expansion of the industry over time. In the maritime transportation area, Xu (2021) used evolutionary game theory to link three major stakeholders, namely the government, port enterprises, and liner companies, to explore their strategic choice mechanisms in the shore power system and observe the impact on the strategic choice of different stakeholders through numerical simulation [30].

Through the above studies on the evolutionary game, it is not difficult to see that evolutionary game theory can involve many aspects. However, the use of evolutionary games in SMTPs is still limited. Traditional game theory regards the participants of the game as rational economic men. In reality, each subject is certainly finitely rational and affected by different circumstances and constraints. Therefore, when considering the game situation between the US and Iran in the Strait of Hormuz, this research considers the constraints of the geographic and military capabilities of the two governments during the game and establishes an asymmetric evolutionary game model. Replicated dynamic equations and the Jacobi matrices are used to determine the stability of the equilibrium point. Finally, assignment simulations are used to identify the key influencing factors affecting the choice of strategy.

3. Analysis of US–Iran Geopolitics

3.1. The Historical Conflict between the United States and Iran

The Strait of Hormuz is located between the southern part of Iran and Oman and connects the Persian Gulf and the Gulf of Oman. According to the statistics of Energy Information Administration, the Strait of Hormuz is responsible for nearly 40% of the world's oil exports. Due to the importance of this passage, its control or severance would have an immeasurable impact on the world economy. The US has a long history of fighting with Iran in the Strait of Hormuz region. As early as 1979, there was an international uproar when 66 US diplomats were detained in Iran during the "Islamic Revolution" [31]. The frequent attacks on oil tankers in the Persian Gulf, between 1984 and 1988 during the Iran-Iraq war, led to a steady rise in the price of crude oil. In 1987 the US launched the "Operation Earnest Will" to protect Kuwaiti-owned tankers from Iranian attacks.

Frequent military manoeuvres between the US and Iran in the Strait of Hormuz in early 2008 led to another confrontation between the two sides. Iran is a closer country to the strait, but it is not necessarily a wise strategy to block the strait. As the throat of world transportation, the Strait of Hormuz has a great economic and military value and is one of the most important maritime transport passages in China's BRI. There is no doubt that if the Iranian government chooses to block the strait, it will certainly hurt the interests of many relevant countries. This move would certainly not be accepted by the international community and may even be met with countermeasures by other countries. From 2003 to 2009, Iran tried to avoid friction with other countries and stopped threatening to block the Strait of Hormuz through constant friendly contacts with Western countries [32].

Iran had maintained an attitude of opposition to the US's withdrawal from the nuclear deal, stressing the need to maintain stability in the Gulf and the Middle East. Currently, on the nuclear issue, Russia is opposed to the US administration's withdrawal and maintains consultations with Iran. The US and Iran can only continue to test and pressure each other in various fields, which may complicate the situation due to the influence of external forces. With stakeholders increasingly joining the game, it will make the situation even more complex. The US and Iran need to be more careful in their decision making [33]. Therefore, when modelling the evolutionary game, this study will not consider both sides actively choosing the strategy of military strikes but rather the strategy of mutual pressure through force deterrence and a certain degree of conflict.

3.2. Impact of Relative Position and Geographical Location

After the end of the Cold War, the US government has always been the superpower in the world. Its economic and military capabilities are far ahead of Iran. With the changes in the international situation, especially after the establishment of the Islamic Republic, the relationship between the US and Iran has continued to deteriorate. The US government has been seeking to expand its influence strategically. Especially after the US government put forward the "State Participation and Expanding Security Strategy" in 1994, it paid more attention to the Strait of Hormuz. From an energy point of view, non-renewable resources, such as oil and gas, are becoming increasingly important to all countries. Iran has always relied on its natural advantages in the geographical location to obtain rich resources, and it exports a large amount of oil every year. Iran has one of the largest remaining recoverable oil reserves in the world. In case of a global oil shortage, Iran's rich oil resources have also become a solid backing for its international status. From the perspective of military strength, Iran is a country where the regular army and the Revolutionary Guards coexist. Although the Iranian government's armed forces have made considerable progress, overall, they are still backward in terms of armament and information technology [34,35].

From a geographical point of view, Iran is located in the centre of the Middle East. Iran has many neighbouring countries such as Turkey, Pakistan, and Armenia. The southern part of the country is close to the Persian Gulf and the Gulf of Oman. At the same time, Iran holds the Strait of Hormuz and controls the main oil export routes throughout the Middle East. It is the intersection of the maritime interests of Eastern and Western countries. Therefore, Iran's geographic location is of extreme importance. Compared with the US, which is far away from the Strait of Hormuz, the investment of its military forces would take a great deal of time and money. Iran's large land area and the national defence border are separated by mountains, which has a significant impact on the entry of the US mechanized army; Iran's complex terrain is likely to trap the US military in a quagmire [36].

It can be seen from the above review that there is a big gap in military strengths between Iran and the US. Once a conflict arises between the two sides, the US government needs to be mindful of the terrain and geographical location of Iran, except for the need to invest a significant amount of manpower and material resources. If Iran chooses to block the Strait of Hormuz, both sides will incur huge economic losses. In addition, this behaviour will also result in losses for other countries either invested or interested in the area, and pressure from the international community will be almost inevitable. Therefore, although both the US and Iran have shown tough attitudes, fundamentally speaking, neither side wants a war to break out.

3.3. The applicability of Evolutionary Game in the US–Iran Game

In evolutionary games, the object of study is the behaviour of a game between one or more groups, and the strategies chosen by the groups affect each other. The game between two countries cannot necessarily be completed by one decision maker. When each country makes strategic choices, every individual in the government must study each strategy and show their own opinions. The government will consider the tactics that the competitor is likely to employ when making decisions. On this basis, it will choose the most suitable way from its own set of strategies to respond. From the view of an evolutionary game that allows sudden changes in the players, each individual in the government will have their own ideas and the strategies proposed will vary. Other relevant individuals will also analyse this strategy and make their own choices, which makes the model more relevant to the actual situation.

Considering the premise assumptions of evolutionary games, each government's choice of strategy is influenced by factors such as military capability, economic capability, and geographical location. As a result, it is impossible to directly determine which strategy will yield the greatest benefit to itself. The players participating in the game are all bounded rationally. Individuals in the government will consider the benefits of this game from a holistic perspective after making their own decisions and make their own choices again, thus eventually tending to a stable strategy. Therefore, it is appropriate to use the evolutionary game model to play games between countries.

From the perspective of the constraints of the evolutionary game, the game between the US and Iran has conditions that affect each other, such as military, economic, and geographical ones. Iran may have concerns due to the strong military capabilities of the US, and the US may also have concerns about the convenience of Iran's geographical location. In the evolutionary game model of the US–Iran game, the key factors can be obtained for each influence by changing the numerical size of the parameters of each influence for both countries. Through the above analysis, it is possible to see whether it is the premise hypothesis of the evolutionary game, the mutual restraint between the two sides of the game, or the particularity of the research object.

4. Evolutionary Game Model

In the game between the US government and the Iranian government in the Strait of Hormuz, the two parties have different international status. Under the current international situation, the attention of both the major EU countries and major powers, such as Russia, have undoubtedly made regional issues gradually more complicated. Therefore, the strategy of force deterrence is employed to conduct game analysis instead of the strategy of military strikes. Before the two governments choose their strategies, they are both in their different complex environments, and they cannot acquire complete information from the other government. In terms of keeping the Strait of Hormuz open for trade, the US government may adopt a deterrence strategy to put pressure on Iran. In this case, the Iranian government may choose a compromise strategy or an uncompromising strategy that is threatening to interfere with transportation. Therefore, an asymmetric evolutionary game model is established.

4.1. Assumptions

It is assumed that each government has incomplete information about the game and is bounded rationally. Both governments make decisions at an initial phase with a certain probability. This then allows them to learn and change their strategy after the decision has been made. The set of strategies of each subject in the game is defined as follows: the US government strategy is {Abandon, Deterrence}; the Iranian government strategy is {Compromising, Interference}. Both groups have their own goals to obtain more national interests as economic men.

Let v_1 represent the basic income obtained by the US government in the Strait of Hormuz, which refers to the basic income obtained by the US government through the transportation of goods and energy in this Strait. In the same way, v_2 represents the basic income obtained by the Iranian government in the Strait of Hormuz. If the two countries compete over the strait, their respective income will be changed. Δc_1 indicates the loss of the US's strategic interests in the Strait of Hormuz if it chooses the abandon strategy when it is interfered by the Iranian government. Similarly, Δc_2 indicates the loss of Iran's strategic interests in the Strait of Hormuz if it chooses compromise strategy when it is deterred by the US government. According to the current importance of the Strait of Hormuz for each, the following can be stated: $\Delta c_1 < \Delta c_2$. β_1 and β_2 are introduced respectively to represent the conflict losses caused by the combined deterrence and interference strategies of the US and Iran. According to the analysis of the military power of both sides in Section 3, the following can be stated: $\beta_1 < \beta_2$. Given the difference in geographic location between the two countries and the different levels of dependence of the two governments on the Strait of Hormuz, let Δ_1 denote the excess gains to the US government when the US government deters and the Iranian government chooses to compromise, and let Δ_2 denote the excess income of the Iranian government when the Iranian government chooses to interfere, and the US government chooses to abandon. According to the analysis of Section 3, Δ_1 is smaller than Δ_2. If the Iranian government chooses an interference strategy, the interests of China and other related countries will be affected. It will damage Iran's international relationship with the relevant countries. Let α indicate Iran's additional loss of income from an intense international relationship. The definition of parameters is shown in Table 1.

Table 1. Definition of parameters.

Parameters	Definitions
v_1	US government's basic income through transportation in the Strait of Hormuz
v_2	Iranian government's basic income through transportation in the Strait of Hormuz
Δc_1	Loss of equity for the US government when choosing abandon strategy
Δc_2	Loss of equity for the Iranian government when choosing compromise strategy
β_1	Conflict losses for the US government
β_2	Conflict losses for the Iranian government
Δ_1	The excess income of the US government
Δ_2	The excess income of the Iranian government
α	Additional losses when the Iranian government chooses interference strategy

4.2. Replicated Dynamic Equations for the Model

When the combination of the two governments' strategies is (Abandon, Compromise), the two countries choose the way of cooperation for common development on the issue of the Strait of Hormuz. In this case both sides receive some basic gain by relying on transport trade in the Strait of Hormuz. Therefore, the gain to the US government in this case is v_1; the gain to the Iranian government is v_2. When the combination of the two governments' strategies is (Deterrence, Compromise), the US government is not interfered by the Iranian government in this case and is able to achieve some excess income in its economy due to the Iranian government's compromise. Therefore, the income for the US government in this case is $v_1 + \Delta_1$. At the same time, the Iranian government will lose its national strategic interests and suffer a certain loss of rights and interests due to the compromise strategy. Therefore, the gain for the Iranian government at this point is $v_2 - \Delta c_2$. When the strategy combination of the two governments is (Abandon, Interference), the Iranian government can obtain a certain amount of excess income. However, if the Iranian government interferes with the strait, the interests of other countries using the strait will be affected besides the US. It will be isolated by the international community and will suffer a certain degree of loss, represented by α. Therefore, the gain for the Iranian government in this case is $v_2 + \Delta_2 - \alpha$. The US government will suffer some loss of equity Δc_1 in this case. Therefore, the gain for the US government here is $v_1 - \Delta c_1$ when the combination of the two governments' strategies is (Deterrence, Interference). This is when both governments do not want to make concessions in the Strait of Hormuz and can only put pressure on each other through force deterrence. Therefore, both sides will suffer different degrees of conflict losses in this case, represented by β_1 and β_2, respectively. Thus, the income for the US and Iran are $v_1 - \beta_1$ and $v_2 - \beta_2 - \alpha$, respectively. According to the above analysis of each case, a game payoff matrix between the US government and the Iranian government is established as shown in Table 2.

Table 2. US–Iran game payoff matrix.

		Iranian Government	
		Interference (y)	Compromise ($1 - y$)
US government	Deterrence (x)	$(v_1 - \beta_1,\ v_2 - \beta_2 - \alpha)$	$(v_1 + \Delta_1, v_2 - \Delta c_2)$
	Abandon ($1 - x$)	$(v_1 - \Delta c_1,\ v_2 + \Delta_2 - \alpha)$	$(v_1,\ v_2)$

It is assumed that in the initial period of the game, the individuals in each government are bounded rationally. The probability of choosing a deterrent strategy for the US government is $x(x\epsilon\ [0,1])$, and the probability of choosing abandonment is $(1 - x)$. The probability of choosing interference for the Iranian government is $y(y\epsilon\ [0,1])$, then the probability of choosing compromise is $(1 - y)$.

From the benefits of each case in the payoff matrix, the expected benefits of the US government can be calculated. The expected revenue of the US government is denoted as u_{11} when choosing the deterrence strategy Equation (1) and u_{12} when the US government chooses the abandonment strategy Equation (2). Its average revenue is denoted as $\overline{u_1}$. Their expected revenues and average revenue are shown in Equations (1)–(3), respectively:

$$u_{11} = y(v_1 - \beta_1) + (1 - \mathrm{y})(v_1 + \Delta_1) \tag{1}$$

$$u_{12} = y(v_1 - \Delta c_1) + (1 - y)v_1 \tag{2}$$

$$\overline{u_1} = xu_{11} + (1 - x)u_{12} \tag{3}$$

According to the dynamic formula of replication in the evolutionary game theory, the dynamic equation of replication of the US government can be derived as Equation (4):

$$\frac{dx}{dt} = x(u_{11} - \overline{u_1}) = x(1 - x)[\Delta_1 - y(\Delta_1 + \beta_1 - \Delta c_1)] \tag{4}$$

Similarly, the expected revenue is denoted as u_{21} when the Iranian government chooses the disruption strategy and u_{22} when the Iranian government chooses the compromise strategy. Its average avenue is denoted as $\overline{u_2}$. Their expected revenues and average revenue are shown in Equations (5)–(7), respectively:

$$u_{21} = x(v_2 - \beta_2 - \alpha) + (1 - x)(v_2 + \Delta_2 - \alpha) \tag{5}$$

$$u_{22} = x(v_2 - \Delta c_2) + (1 - x)v_2 \tag{6}$$

$$\overline{u_2} = yu_{21} + (1 - y)u_{22} \tag{7}$$

Similarly, the replication dynamic equation for the Iranian government can be derived as Equation (8):

$$\frac{dy}{dt} = y(u_{21} - \overline{u}_2) = y(1 - y)[\Delta_2 - \alpha - x(\Delta_2 + \beta_2 - \Delta c_2)] \tag{8}$$

Coupling the replicated dynamic equations of the US government with those of the Iranian government yields a two-dimensional dynamic system, as shown in Equation (9).

$$\begin{cases} \frac{dx}{dt} = x(u_{11} - \overline{u_1}) = x(1 - x)[\Delta_1 - y(\Delta_1 + \beta_1 - \Delta c_1)] \\ \frac{dy}{dt} = y(u_{21} - \overline{u}_2) = y(1 - y)[\Delta_2 - \alpha - x(\Delta_2 + \beta_2 - \Delta c_2)] \end{cases} \tag{9}$$

5. Evolutionary Stability Analyses

5.1. Evolutionary Game Analysis of US–Iran Mixed Strategy

According to Freidman's idea, the stability of equilibria is determined by the rank and trace of the Jacobi matrix of the dynamic system. A combination of mixed strategies is a stable strategic equilibrium when the rank of the matrix is greater than 0 and the trace of the matrix is less than 0 [37]. Let the two equations in the two-dimensional dynamic system be zero to find their equilibrium points. Thus, the five equilibria points are calculated as:

$$\text{E1}(0,0),\ \text{E2}(0,1),\ \text{E3}(1,0),\ \text{E4}(1,1),\ \text{E5}\left(\frac{\Delta_2 - \alpha}{\Delta_2 + \beta_2 - \Delta c_2}, \frac{\Delta_1}{\Delta_1 + \beta_1 - \Delta c_1}\right)$$

These equilibria vary in their stability in different situations. Their evolved positions may also change once the probability of the US government or the Iranian government's choice of strategy changes. In order to analyse the stability of these points, the Jacobian matrix is established as Equation (10).

$$J = \begin{bmatrix} \frac{\partial \frac{dx}{d_t}}{\partial x} & \frac{\partial \frac{dx}{d_t}}{\partial y} \\ \frac{\partial \frac{dy}{d_t}}{\partial x} & \frac{\partial \frac{dy}{d_t}}{\partial y} \end{bmatrix} \tag{10}$$

Combining Equations (9) and (10), Equations (11)–(14) are obtained:

$$\frac{\partial \frac{d_x}{d_t}}{\partial x} = (1 - 2x)[\Delta_1 - y(\Delta_1 + \beta_1 - \Delta c_1)] \tag{11}$$

$$\frac{\partial \frac{d_x}{d_t}}{\partial y} = x(1 - x)(\Delta_1 + \beta_1 - \Delta c_1) \tag{12}$$

$$\frac{\partial \frac{d_y}{d_t}}{\partial x} = y(1 - y)(\Delta_2 + \beta_2 - \Delta c_2) \tag{13}$$

$$\frac{\partial \frac{d_y}{d_t}}{\partial y} = (1 - 2y)[\Delta_2 - \alpha - x(\Delta_2 + \beta_2 - \Delta c_2)] \tag{14}$$

Then the Jacobian matrix can be written as Equation (15):

$$J = \begin{bmatrix} (1-2x)[\Delta_1 - y(\Delta_1 + \beta_1 - \Delta c_1)] & x(1-x)(\Delta_1 + \beta_1 - \Delta c_1) \\ y(1-y)(\Delta_2 + \beta_2 - \Delta c_2) & (1-2y)[\Delta_2 - \alpha - x(\Delta_2 + \beta_2 - \Delta c_2)] \end{bmatrix} \quad (15)$$

By calculating the rank and trace of the Jacobian matrix in Equation (15), Equations (16), and (17) are obtained:

$$\begin{aligned} Det\ J = {} & (1-2x)[\Delta_1 - y(\Delta_1 + \beta_1 - \Delta c_1)](1-2y)[\Delta_2 - \alpha - x(\Delta_2 + \beta_2 - \Delta c_2)] \\ & - x(1-x)(\Delta_1 + \beta_1 - \Delta c_1)y(1-y)(\Delta_2 + \beta_2 - \Delta c_2) \end{aligned} \quad (16)$$

$$Tr\ J = (1-2x)[\Delta_1 - y(\Delta_1 + \beta_1 - \Delta c_1)] + (1-2y)[\Delta_2 - \alpha - x(\Delta_2 + \beta_2 - \Delta c_2)] \quad (17)$$

5.2. Evolutionary Stability Strategies in Different Scenarios

Analysis of Equation (16) shows that when the parameters in the game payoff matrix have different relative magnitude relationships, the positive and negative rank and trace of the matrix can be different. The scenarios are divided according to the amount of conflict losses suffered by the US government, the degree of sanctions on the Iranian government by the international community within its acceptable range, and the importance of the Strait of Hormuz to Iran's strategic interests.

From the perspective of the US government, when the US military strength is far stronger than that of Iran, $\beta_1 < \Delta c_1$. The US suffers less loss of equity at this time, which is probably because the two parties are not interfering with each other at the time of the conflict. The losses to the US government in this situation are not very large. At the same time, the losses in terms of strategic and economic benefits are not very significant. In terms of the Iranian government's choice of interference strategy, the US government suffers less conflict loss than equity loss. For Iran, in this case, the relationship between the magnitude of the Iranian government's conflict losses and equity losses is not determinable. It is necessary to conduct a detailed analysis of the two situations of $\Delta c_2 < \alpha + \beta_2$ and $\Delta c_2 > \alpha + \beta_2$ to analyse the rank and trace of the Jacobian matrix and to obtain the stable strategy after evolution.

Similarly, if the two sides are in conflict and the US government is negatively affected by some factors such as geographical location and interference from other countries, then $\beta_1 > \Delta c_1$. It is important to note that in the above scenario the Iranian government must consider the impact on the interests of the countries concerned, such as China when choosing its disruption strategy and the additional losses it suffers as a result. Therefore, the relative magnitude of Δ_2 and α needs to be discussed further.

In terms of the relative size of the Iranian government's losses, it may be subject to intervention by other countries when the US plays the game with Iran. The conflict losses suffered by the Iranian government in choosing the interference strategy are small when compared to the equity losses. In this case, when the US government chooses an abandon strategy, it can obtain a certain amount of excess income for the Iranian government, $\Delta c_2 > \alpha + \beta_2$.

When $\Delta c_2 < \alpha + \beta_2$, in the absence of intervention by other countries following a conflict between the two sides, the Iranian government will suffer more if it chooses an interference strategy than if it chooses a compromise strategy.

In summary, the above scenarios are all possible ones that could occur in the Strait of Hormuz. It can be more comprehensively analysed that in different game conditions, the loss caused by different factors will affect the choice of the two governments' strategies. Similarly, the different importance between the parameters of the variables in the model can be combined into eight different scenarios and the stability of each equilibrium point is shown in Table 3.

Scenario 1. In this scenario, the US government is militarily more capable of resolving the problem quickly with less conflict losses and the international community has a greater impact on the Iranian government's sanctions. That is ß$_1 < \Delta c_1$, $\Delta_2 < \alpha$ and $\Delta c_2 < \alpha +$ ß$_2$. In the system, only E3(1,0) is a stable point, E2(0,1) is an unstable point, and E1(0,0), E4(1,1) are saddle points. Therefore, in this scenario the system will gradually converge to the E3(1,0) point over time. This strategy combination of the US and Iran is (Deterrence, Compromise).

Scenario 2. The US government would have more conflict losses and international community sanctions against the Iranian government once the US government conflicts with Iran. Meanwhile, Iran believes that the strategic importance of the Strait of Hormuz is more important than its own losses, $\beta_1 > \Delta c_1$, $\Delta_2 < \alpha$, and $\Delta c_2 > \alpha + \beta_2$. All equilibrium points in the system do not satisfy the stability condition. As a result, there is no evolutionary stability strategy in this scenario.

Scenario 3. Scenario 3 is similar to scenario 1 except that Iran considers the Strait of Hormuz to be more important. There exist $\beta_1 < \Delta c_1$, $\Delta_2 < \alpha$ and $\Delta c_2 > \alpha + \beta_2$. In this case, only E4(1,1) is the stable point in the system and E2(0,1) is the unstable point while E1(0,0) and E3(1,0) are saddle points. Therefore, in this scenario, the system will gradually converge to E4(1,1). This strategy combination of the US and Iran is (Deterrence, Interference).

Scenario 4. When $\beta_1 < \Delta c_1$, $\Delta_2 > \alpha$ and $\Delta c_2 < \alpha + \beta_2$, the US government is militarily more capable of resolving the problem quickly with less conflict losses and the international community's sanctions have little impact on the Iranian government. In this case, only E3(1,0) is the stable point and E1(0,0) is the unstable point while E2(0,1) and E4(1,1) are saddle points in the system. Therefore, in this scenario, the system will gradually converge to the E3 point, that is, the strategic combination of the US and Iran is (Deterrence, Compromise).

Scenario 5. When $\beta_1 < \Delta c_1$, $\Delta_2 > \alpha$ and $\Delta c_2 > \alpha + \beta_2$, the US government is militarily more capable of resolving the problem quickly with less conflict losses and the international community's sanctions have little impact on the Iranian government. In this system, E4(1,1) is the stable point; E2(0,1) and E3(1,0) are saddle points; E1(0,0) is the unstable point. Therefore, in this scenario, the system will gradually converge to E4(1,1); the strategic combination of the US and Iran is (Deterrence, Interference).

Scenario 6. When $\beta_1 > \Delta c_1$, $\Delta_2 < \alpha$ and $\Delta c_2 < \alpha + \beta_2$, the US would have more conflict losses once a conflict with Iran arises. At the same time the international community's sanctions against the Iranian government have a greater impact. In this case, in the system, E3(1,0) is the stable point and E4(1,1) is the unstable point while E1(0,0) and E2(0,1) are saddle points. The system will gradually converge to the E3(1,0) point, that is, the strategic combination of the US and Iran is (Deterrence, Compromise).

Table 3. Stability of equilibrium points of scenarios 1–8.

Scenario	Equilibrium	Det J	Tr J	Stability	Scenario	Equilibrium	Det J	Tr J	Stability
1	E1(0,0)	−	±	Saddle	5	E1(0,0)	+	+	Unstable
	E2(0,1)	+	+	Unstable		E2(0,1)	−	±	Saddle
	E3(1,0)	+	−	Stable		E3(1,0)	−	±	Saddle
	E4(1,1)	−	±	Saddle		E4(1,1)	+	−	Stable
2	E1(0,0)	−	±	Saddle	6	E1(0,0)	−	±	Saddle
	E2(0,1)	−	±	Saddle		E2(0,1)	−	±	Saddle
	E3(1,0)	−	±	Saddle		E3(1,0)	+	−	Stable
	E4(1,1)	−	±	Saddle		E4(1,1)	+	+	Unstable
3	E1(0,0)	−	±	Saddle	7	E1(0,0)	+	+	Unstable
	E2(0,1)	+	+	Unstable		E2(0,1)	+	−	Stable
	E3(1,0)	−	±	Saddle		E3(1,0)	+	−	Stable
	E4(1,1)	+	−	Stable		E4(1,1)	+	+	Unstable
4	E1(0,0)	+	+	Unstable	8	E1(0,0)	+	+	Unstable
	E2(0,1)	−	±	Saddle		E2(0,1)	+	−	Stable
	E3(1,0)	+	−	Stable		E3(1,0)	−	±	Saddle
	E4(1,1)	−	±	Saddle		E4(1,1)	−	±	Saddle

Scenario 7. In this scenario, the US would have more to lose once a conflict with Iran arises. Meanwhile the Iranian government is less influenced by the international community. That is $\beta_1 > \Delta c_1$, $\Delta_2 > \alpha$ and $\Delta c_2 < \alpha + \beta_2$. In this case, there are two stable points E2(0,1) and E3(1,0) in the system, and E1(0,0) and E4(1,1) are unstable points. It shows that the loss of the system when conflict occurs for both the US and Iran currently is very huge, and the system gradually converges to E2(0,1) or E3(1,0).

Scenario 8. Scenario 8 is similar to scenario 7 except that Iran considers the Strait of Hormuz to be more important for itself, $\beta_1 > \Delta c_1$, $\Delta_2 > \alpha$ and $\Delta c_2 > \alpha + \beta_2$. As shown in Table 3, the system has only one stable point E2(0,1), with E1(0,0) being the unstable point, and E3(1,0) and E4(1,1) being saddle points. The system will eventually converge to point E2(0,1).

6. Simulation and Discussion

6.1. Numerical Simulation

The evolutionary path of the game is obtained by using numerical simulation of the probability of the game subject's choice of strategy in each case, based on the relationship between the magnitude of each parameter in the payoff matrix in Section 5 for the eight scenarios. The evolutionary path of the game contributes to showing the influence of each parameter on the game.

Scenario 1. According to the definition of scenario 1 in Section 5, the combination of strategies is (Deterrence, Compromise); the US government obtains excess income $\Delta_1 = 20$, Due to the difference in the dependence of the two countries on this passage, there is $\Delta_1 < \Delta_2$, assuming $\Delta_2 = 25$. In terms of conflict losses, assume that the loss suffered by the US government $\beta_1 = 10$, since the difference in military power between the two sides there is $\beta_1 < \beta_2$, assuming $\beta_2 = 20$. In terms of equity loss, it is assumed that the US government suffers an equity loss of $\Delta c_1 = 15$ as the importance of the passage to both sides differs in terms of their respective strategies with $\Delta c_1 < \Delta c_2$, assuming $\Delta c_2 = 20$. Furthermore, based on the constraint on α in this scenario, assuming $\alpha = 30$, the evolutionary path diagram in this scenario is shown in Figure 1. The diagram shows that both subjects involved in the game eventually converge to the equilibrium point (1,0). In this scenario, both sides end up with a combination of decisions to exert pressure on each other, regardless of the initial states of x and y. This is because the US government's conflict losses in this scenario are lower than its equity losses. Once the two sides conflict, Iran suffers high conflict losses and some additional losses when it chooses to interfere.

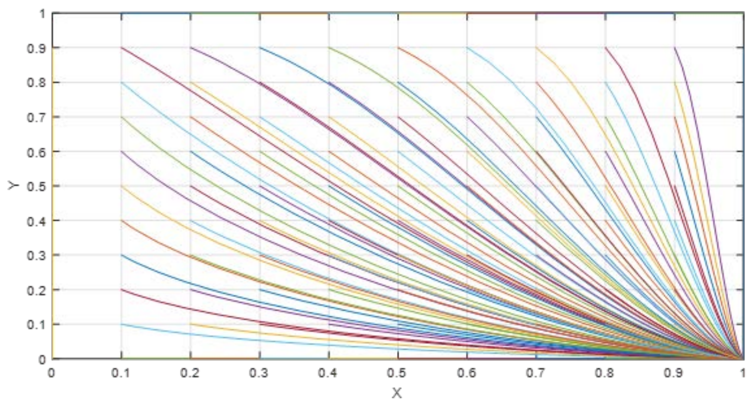


Figure 1. Evolutionary path diagram when $\beta_1 < \Delta c_1$, $\Delta_2 < \alpha$, $\Delta c_2 < \alpha + \beta_2$ (Deterrence, Compromise).

Scenario 2. In this scenario, the two sides of the game cannot form a stable combination of strategies. In the same way used in scenario 1, each parameter is assigned with numbers that can satisfy its corresponding condition, assuming that $\Delta_1 = 10$, $\beta_1 = 15$, $\Delta c_1 = 10$, $\Delta_2 = 15$, $\alpha = 20$, $\beta_2 = 20$, $\Delta c_2 = 45$. The simulation diagram in this scenario is shown in Figure 2. The graph shows that the probability of the US and Iran choosing each strategy changes over time, eventually forming a wavy curve. This indicates that the probability size of each party's choice of strategy is dependent on the other party's choice, which affect each other, and this ultimately does not lead to a stable strategy.

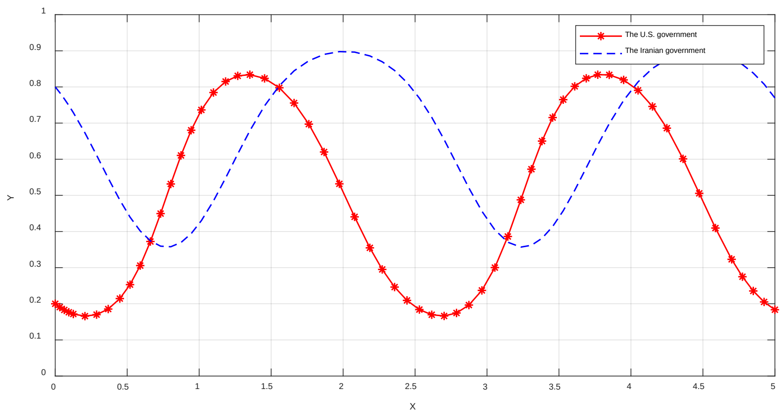
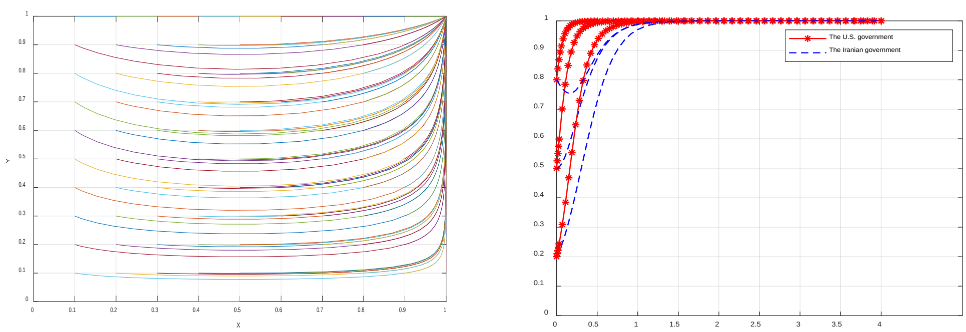


Figure 2. Evolutionary path diagram when $\beta_1 > \Delta c_1, \Delta_2 < \alpha, \Delta c_2 > \alpha + \beta_2$ (no evolutionary stability).

Scenario 3. In scenario 3, the result of the evolutionary equilibrium is (Deterrence, Interference). Each parameter is assigned with numbers that can satisfy its corresponding condition, assuming that $\Delta_1 = 20$, $\beta_1 = 10$, $\Delta c_1 = 15$, $\Delta_2 = 25$, $\alpha = 30$, $\beta_2 = 15$, $\Delta c_2 = 50$. The simulation diagram in this case is shown in Figure 3. Figure 3a shows that no matter how the values of x and y change, they eventually converge on the strategy combination (Deterrence, Interference). In Figure 3b, when the probability of Iran's initial state is 0.8, the probability of disruption decreases during the first period of the game and then gradually starts to increase, as the Iranian government's equity loss is lower than the conflict loss, which makes the Iranian government prefer a compromise strategy.

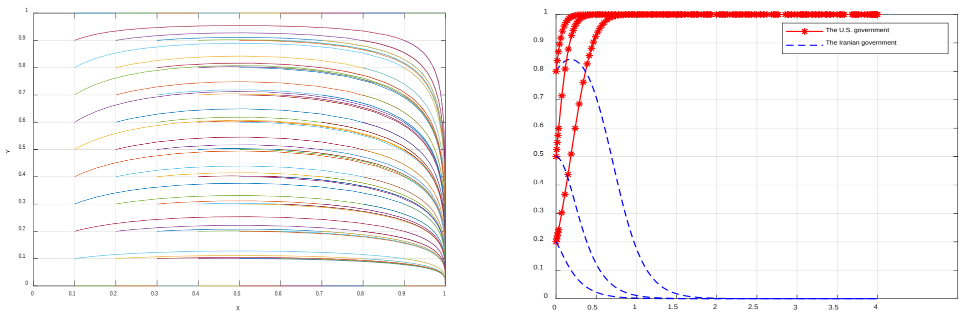


(**a**) Evolutionary path diagram (**b**) Evolutionary paths with different initial probabilities

Figure 3. Evolutionary path diagram when $\beta_1 < \Delta c_1, \Delta_2 < \alpha, \Delta c_2 > \alpha + \beta_2$ (Deterrence, Interference).

Scenario 4. The evolutionary equilibrium in this scenario is (Deterrence, Compromise). Similar to the previous scenarios, assume that $\Delta_1 = 20$, $\beta_1 = 10$, $\Delta c_1 = 15$, $\Delta_2 = 25$, $\alpha = 20$, $\beta_2 = 15$, $\Delta c_2 = 30$. The simulation diagram in this case is shown in Figure 4a. Iran's evolution paths with different initial probabilities are shown in Figure 4b. For the Iranian government there is a tendency for the probability to increase for a period when the initial value is larger, after which it will gradually converge towards a compromise strategy.

Scenario 5. The result of the evolutionary equilibrium in this scenario is (Deterrence, Interference). In a similar way, assume that $\Delta_1 = 20$, $\beta_1 = 10$, $\Delta c_1 = 15$, $\Delta_2 = 25$, $\alpha = 20$, $\beta_2 = 15$, $\Delta c_2 = 40$. The simulation diagram in this case is shown in Figure 5. In this scenario, the conflict loss of both parties is less than the loss of equity. Evolutionary paths do not fluctuate over time when the initial probability varies. When the initial probability of the US government is low, it can converge to the deterrence strategy at a rapid rate. For the Iranian government, although it converges to the interference strategy in the end, it needs to consider the magnitude of the loss, α.



(**a**) Evolutionary path diagram (**b**) Evolutionary paths with different initial probabilities

Figure 4. Evolutionary path diagram when $\beta_1 < \Delta c_1, \Delta_2 > \alpha, \Delta c_2 < \alpha + \beta_2$ (Deterrence, Compromise).

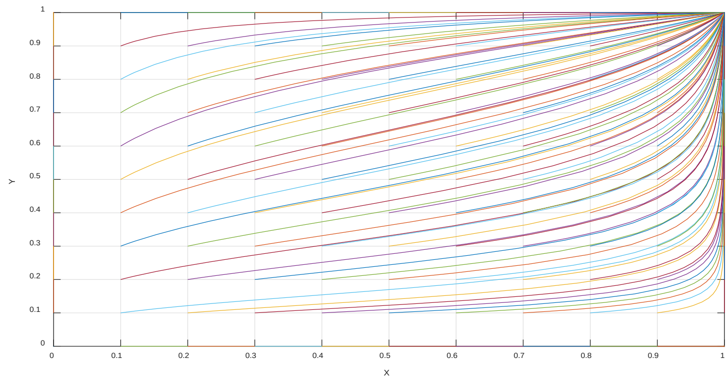


Figure 5. Evolutionary path diagram when $\beta_1 < \Delta c_1, \Delta_2 > \alpha, \Delta c_2 > \alpha + \beta_2$ (Deterrence, Interference).

Scenario 6. The result of the evolutionary equilibrium in this scenario is (Deterrence, Interference). In a similar way, assume $\Delta_1 = 20$, $\beta_1 = 15$, $\Delta c_1 = 10$, $\Delta_2 = 25$, $\alpha = 30$, $\beta_2 = 20$, $\Delta c_2 = 30$. The simulation diagram in this case is shown in Figure 6. The graph shows that there are significant fluctuations when the initial probabilities of both sides are high. As time progresses, y gradually converges to the compromise strategy, and x gives up the strategy first. As the probability of y gradually decreases, x will eventually converge to the deterrence strategy. The situation arises because the US government's conflict losses are higher than its equity losses. When the Iranian government has a high probability of choosing an interference strategy, the US government will give priority to choosing the abandonment strategy. The Iranian government will also suffer from greater conflicts, which will gradually reduce the probability of interference.

Scenario 7. In this scenario, there are two equilibrium points. Its evolutionary equilibrium results are (Deterrence, Compromise) and (Abandon, Interference). Assigning each parameter to satisfy its corresponding condition gives the following: Δ_1 to be 20, β_1 to be 15, Δc_1 to be 10, Δ_2 to be 30, α to be 25, β_2 to be 20, and Δc_2 to be 30. The simulation diagram in this case is shown in Figure 7. From Table 3 it is known that (0,0) and (1,1) are the instability points and that different initial values eventually converge to (1,0) or (0,1) after evolution. In this scenario, the system evolves to continue to converge to its chosen strategy only when its initial probability is high for both sides. As conflict losses are relatively large for both parties, the US and Iran try to avoid conflicts as much as possible. Only when one party is more determined and has a higher probability of choosing a strategy, the game eventually converges on a combination of strategies in its favour after repeated play.

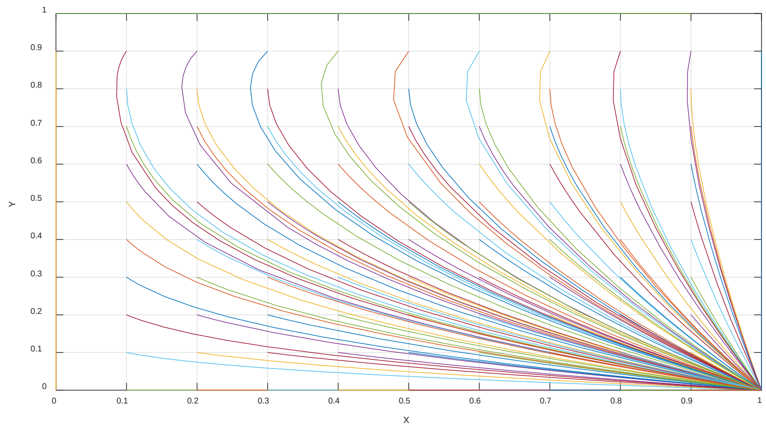


Figure 6. Evolutionary path diagram when $\beta_1 > \Delta c_1, \Delta_2 < \alpha, \Delta c_2 < \alpha + \beta_2$ (Deterrence, Interference).

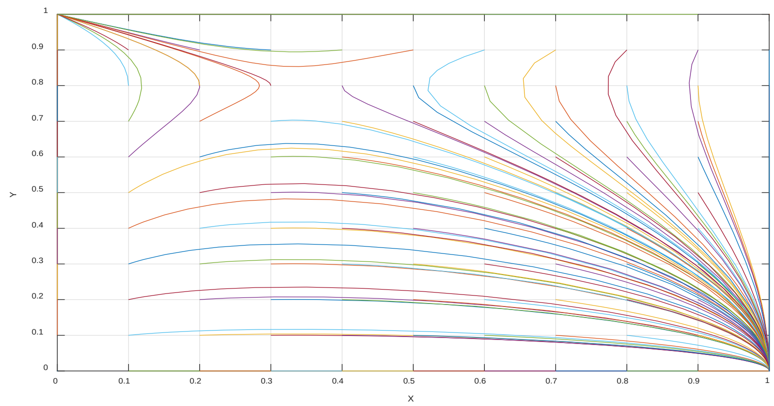


Figure 7. Evolutionary path diagram when $\beta_1 > \Delta c_1, \Delta_2 > \alpha, \Delta c_2 < \alpha + \beta_2$ (Deterrence, Compromise) and (Abandonment, Interference).

Scenario 8. The result of the evolutionary equilibrium in this scenario is (Abandonment, Interference). In a similar way, assuming $\Delta_1 = 20$, $\beta_1 = 15$, $\Delta c_1 = 10$, $\Delta_2 = 30$, $\alpha = 25$, $\beta_2 = 20$, $\Delta c_2 = 45$. The simulation diagram in this case is shown in Figure 8. The probability of the US government's strategy choice in this scenario is more volatile for two reasons. On the one hand, the US government's own conflict losses are higher than its equity losses. On the other hand, there are larger excess returns of the Iranian government in this scenario, which can influence its strategy choice to gradually move towards an interference strategy.

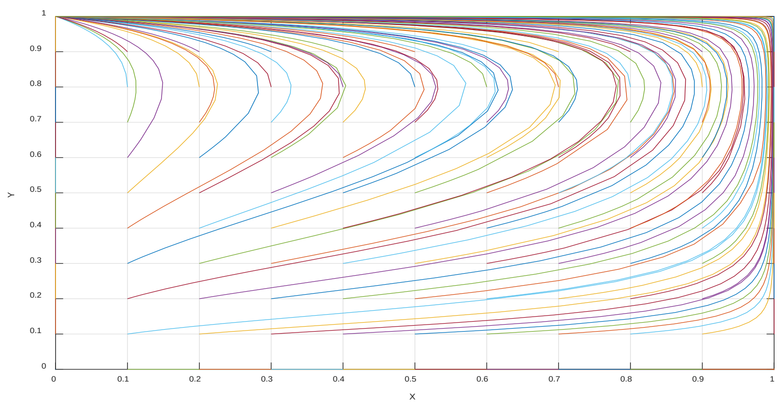
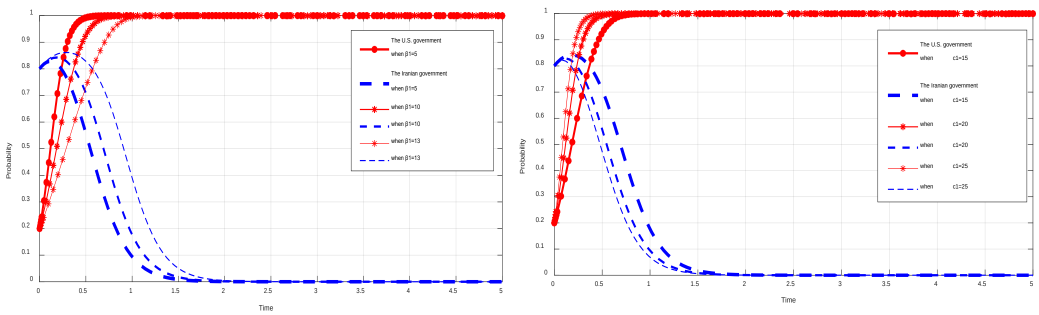


Figure 8. Evolutionary path diagram when $\beta_1 > \Delta c_1, \Delta_2 > \alpha, \Delta c_2 > \alpha + \beta_2$ (Abandonment, Interference).

6.2. Parameter Sensitivity Analysis

From the analysis in the previous section, it is known that the US government and the Iranian government differ in the combination of their stabilization strategies under different conditions. The relative sizes of the parameters of the variables in the model are key to their choice of strategy. Since the changes in the size of each parameter in each scenario will not affect the final stable equilibrium point and the way it changes, this section carries out a sensitivity analysis of the parameters β_1, Δc_1, Δ_2, and α. The impact on the convergence speed of the evolutionary path will be analysed.

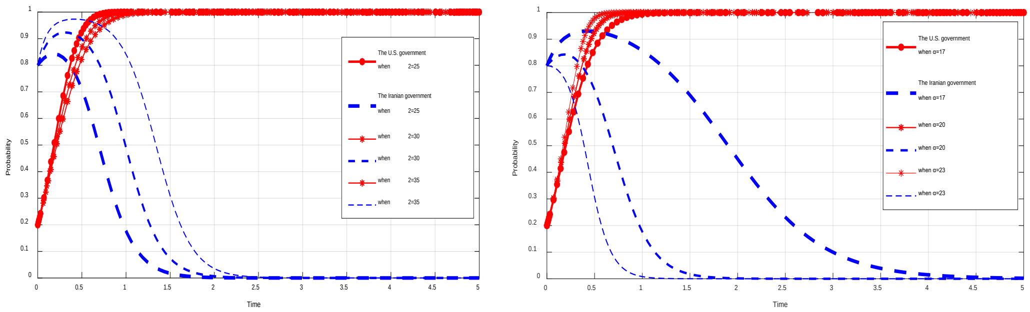
Sensitivity analysis of β_1 and Δc_1. Take the conditions of scenario 4 as an example. When other parameters are fixed, the value range of β_1 is (0,15). Take the values of β_1 as 5, 10, and 13, respectively. The initial state is set as (0.2,0.8), as shown in Figure 9a. It can be seen from Figure 9a that as the value of the parameter gradually increases, and the color of the curve becomes progressively lighter. As the value of β_1 increases, the convergence time becomes longer. When β_1 and other parameters are fixed, the value range of Δc_1 is (10,30). Set the values of Δc_1 as 15, 20, and 25, respectively. As shown in Figure 9b, as the value of Δc_1 gradually increases, it has a certain inhibitory effect on the US government. As for the Iranian government, its convergence time has not changed significantly. It shows that when the conflict loss or loss of rights and interests of the US government gradually increases, it will restrain the US government from making decisions, so that the US government will try to avoid conflicts and protect its rights and interests in the Strait of Hormuz.



(**a**) Sensitivity analysis of β_1 (**b**) Sensitivity analysis of Δc_1

Figure 9. Evolution simulation diagram with different values of β_1 and Δc_1.

Sensitivity analysis of Δ_2 and α. Take the conditions of scenario 4 in the previous section as an example. When other parameters are fixed, the value range of Δ_2 is (20,+∞); take the values of Δ_2 as 25, 30 and 35, and take the initial state as (0.2,0.8), respectively. As the value of Δ_2 increases, the convergence time becomes longer. This indicates that the increase or decrease in excess revenue acts as a disincentive for the Iranian government to choose a compromise strategy. Similarly, the value range of α is (15,25). Take the values of α as 17, 20, and 23, respectively. As shown in Figure 10b, when the value of α increases, there is a clear promotion effect on the Iranian government's choice of compromise strategy. It shows that when the Iranian government chooses the interference strategy, it will affect the interests of other relevant countries in the Strait of Hormuz, thus making itself isolated by the international community and even subject to countermeasures by other countries, which will have a greater impact on its own losses. For China, a large number of cargos pass through the Strait of Hormuz every year. Many of China's transportation interests, including crude oil, consumer goods, and infrastructure investments require transportation and supply from the Middle East and have a high level of dependency. China's "Belt and Road" initiative indicates that for countries along the route, with strong resource and economic complementarities, China needs to enhance trade flows, policy communication, and energy infrastructure connectivity as well as maintain the safety of oil and gas transport passages. If the Strait of Hormuz is blocked, it will have a great impact on China's actual interests.



(**a**) Sensitivity analysis of Δ_2 (**b**) Sensitivity analysis of α

Figure 10. Evolution simulation diagram with different values of Δ_2 and α.

7. Conclusions

This paper introduces an evolutionary game model to analyse the game involving the Strait of Hormuz between the US and Iran. The model analyses the possible strategies that the US and Iran may adopt surrounding the Strait of Hormuz. By establishing the Jacobian matrix and calculating the rank and trace of the matrix, the presented model is divided into eight different game scenarios. The evolutionary stable strategies are discussed.

The results of the game show that only if the US government has a large enough conflict loss will it be possible for the US government to shift to the Abandon strategy. From Iran's perspective, Iran needs to assess the strategic value of the Strait of Hormuz to itself. The system will evolve toward (Abandon, Interference) only if the strategic value of the Strait of Hormuz to Iran is larger than the losses Iran would have to endure and can bring a great enough conflict loss to the US government. It is shown that under the assumption that other countries intervene in the US–Iran dispute, losses incurred by the US can become quite large, and the evolutionary outcome will change significantly if the initial attitude of the Iranian government is very firm. Furthermore, the US government's deterrence strategy can be inhibited when its conflict losses gradually increase. For Iran, the additional losses have a more pronounced dampening effect on Iran's strategy of blocking the strait. Whatever Iran's initial attitude, it will put itself at a disadvantage if it affects the interests of other countries. Finally, an in-depth analysis of the sensitivity of the variable parameters in the model shows that the size of the additional losses for the Iranian government has a greater impact on the choice of its strategy. When the economic interests of various countries are getting closer, the friction between them increases. Therefore, to safeguard the smooth passage through the Strait of Hormuz and the interests of the various countries involved, it is necessary to establish early warning of political frictions on time, as well as gradually improve the international coordination and punishment mechanism to avoid possible conflicts.

This work still has some limitations at present. No perfect method is found to quantify the conflict loss of the two countries under the strategy combination (Deterrence, Interference). Future research may focus on empirical analysis of the game between countries. It is meaningful to analyse the game strategy in combination with the actual international relationship.

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Disclaimer: The authors are solely responsible for the analysis in this paper, which is largely based on hypothetical and judgmental data. This paper is the opinion of the authors and does not represent the belief and policy of their employers.

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